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Search for Physics beyond the Standard Model at the Tevatron

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Abstract. Recent searches for physics beyond the standard model at the Tevatron are reported, with emphasis on supersymmetry.

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INTRODUCTION

This talk is devoted to searches for signals of physics beyond the standard model, performed by the CDF and DØ experiments at the Fermilab Tevatron, where protons and antiprotons collide at a center of mass energy of 1.96 TeV. The results reported here are based on data samples corresponding to integrated luminosities of up to 1.2 fb^{-1}. Details can be found in Ref. [1].

The standard model (SM) is constructed with the following ingredients: a field theory in a four-dimensional space time, with invariance under the Poincaré group; the $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$ gauge group, with electroweak symmetry breaking (EWSB) by the Higgs mechanism; three families of quarks and leptons.

Possible extensions of the SM include: extending the Poincaré group by supersymmetry (SUSY) which, in its local form, allows gravitation to be incorporated in the theory; replacing the field theory by a (super)string theory; increasing the number of space dimensions; embedding the SM gauge group in a larger one, in the framework of grand unified theories (GUTs); introducing new interactions between quarks and leptons, mediated by leptoquarks; invoking alternative mechanisms of EWSB, such as technicolor; attempting to repeat the history of onion peeling in theories of compositeness...

Because of the limited duration of this talk and of the very nature of this conference, I will concentrate on SUSY and extra dimensions, after a brief excursion into GUT motivated searches. All limits will be given at the 95% C.L., and discoveries will be reported only for a level of significance of at least 5σ.

ADDITIONAL GAUGE BOSONS

Additional neutral bosons similar to the Z arise for instance in string inspired GUTs where extra U(1)s result from the breaking of an E(6) group. Such Z' bosons can be produced by the Drell-Yan mechanism, and are best searched via their decay into an

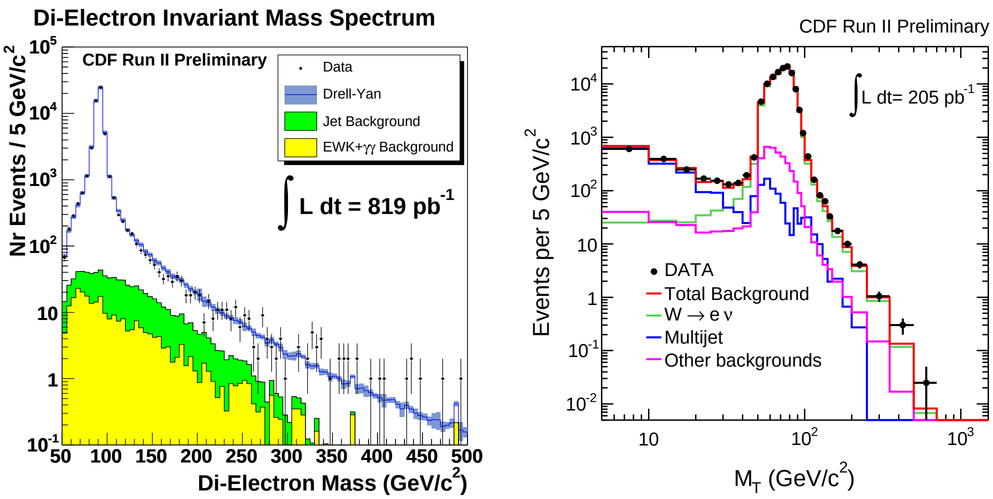


FIGURE 1. Dielectron mass (left) and electron-missing E_T transverse mass (right).

e^+e^- pair because of the low background, compared to $q\bar{q}$ decays, and of the superior mass resolution, compared to $\mu^+\mu^-$ decays. The absence of any peak (other than the Z) in the dielectron mass spectrum observed by CDF in 0.8 fb^{-1} (Fig. 1) allows a lower limit of 850 GeV to be set on a "sequential" Z', i.e. with couplings identical to those of the SM Z boson [2].

Similarly, extra W bosons are expected in left-right symmetric models. The search is performed in the $W' \to e\nu$ channel, where the dielectron mass is replaced by the transverse mass, constructed from the transverse momentum of an isolated electron and the missing transverse energy. No Jacobian peak other than the one from the W is seen (Fig. 1), which yields a W' lower mass limit of 788 GeV, based on 0.2 fb^{-1} of CDF data.

SUPERSYMMETRY

In such a conference, it is probably not appropriate to address questions such as "What is SUSY ?" or "Why SUSY ?". Nor to define squarks or gauginos, or R-parity... I will therefore restrict myself to: "Which SUSY ?".

The Tevatron experiments have investigated various incarnations of SUSY:

- a more or less constrained MSSM (minimal supersymmetric extension of the SM), the most constrained form being mSUGRA (minimal supergravity) controlled by five parameters ($m_0, m_{1/2}, \tan\beta, A_0$ and sign(μ)). A neutralino LSP (lightest SUSY particle), $\tilde{\chi}^0_1$, is assumed. Both R-parity conservation and violation are considered;
- gauge-mediated SUSY breaking (GMSB), with a gravitino LSP and a neutralino NLSP (next to lightest SUSY particle);
- anomaly-mediated SUSY breaking (AMSB), with a wino LSP and a long-lived chargino;
- split-SUSY, with heavy scalars and a long-lived gluino.

Searches in R-parity conserving supergravity inspired models

Detailed analyses were performed in the mSUGRA framework, along two main directions:

- the search for squarks and gluinos, leading to multijet+missing E_T topologies, with large production cross sections but also large instrumental backgrounds;
- the search for electroweak gauginos with leptonic decays, leading to the celebrated trilepton+missing E_T final state, with smaller production cross sections times leptonic branching fractions but with a clean experimental signature.

Charginos and neutralinos [3, 4]. Associated production of the lightest chargino (with $\tilde{\chi}^{\pm} \to \ell\nu\tilde{\chi}_1^0$) and second lightest neutralino (with $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$) lead to final states containing three leptons and missing E_T due to the neutrino and to the weakly interacting $\tilde{\chi}_1^0$s. In spite of its apparent simplicity, this search is challenging because the rates are low, the leptons are soft, and the τ contribution is enhanced at large $\tan\beta$. A large integrated luminosity and the combination of many final states are necessary to reach a relevant level of sensitivity.

The general strategy is to require two isolated electrons or muons and some missing E_T. Channel dependent selection criteria are applied to reject backgrounds, e.g. from $Z \to \ell\ell$. Finally, either the two leptons are required to have the same sign, a configuration in which the SM backgrounds are small, or a third lepton is required, identified or in the form of an isolated track, the latter providing some sensitivity to hadronic τ decays.

In the end, the remaining backgrounds are instrumental, due to lepton misidentification or to fake missing E_T, or irreducible from SM processes such as WZ production. Altogether, the CDF analyses select 11 events while 9.0 ± 1.0 are expected. The corresponding numbers for DØ are 4 and 4.9 ± 1.0. Limits on the production cross section times branching fraction into three leptons were derived, with some model dependence as explained below. For $\tilde{\chi}^{\pm}$ and $\tilde{\chi}_2^0$ masses of 140 GeV, they are at the level of 0.22 pb for CDF and 0.07 pb for DØ. (The corresponding limits expected in the absence of a signal are 0.16 and 0.08 pb.)

To turn these cross section limits into mass limits, specific mSUGRA configurations were considered. In the mass range of interest, the $\tilde{\chi}^{\pm}$ and $\tilde{\chi}_2^0$ decays proceed via virtual W or Z boson exchange, or via slepton exchange. If sleptons are heavy, the leptonic branching fractions are too small to allow any mass limit to be placed. Low slepton mass configurations have been considered by both collaborations: with a value of m_0 fixed at 60 GeV by CDF, with m_0 adjusted such that the slepton masses are just above the $\tilde{\chi}_2^0$ mass by DØ (the "3ℓ-max" scenario); in both cases, slepton masses were set to be equal for the three lepton flavors. The results are shown in Fig. 2. The chargino mass lower limit obtained by DØ in the 3ℓ-max scenario is 146 GeV, well beyond the LEP limit of 103.5 GeV. The CDF limit in the low m_0 scenario they considered is 126 GeV.

Generic squarks and gluinos [5, 6]. If squarks are lighter than gluinos, they are expected to decay according to $\tilde{q} \to q\tilde{\chi}_1^0$, while gluinos are expected to decay according to $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$ if squarks are heavier than gluinos. Jets and missing E_T carried away by the final $\tilde{\chi}_1^0$s is therefore expected from any squark or gluino production. The pair production

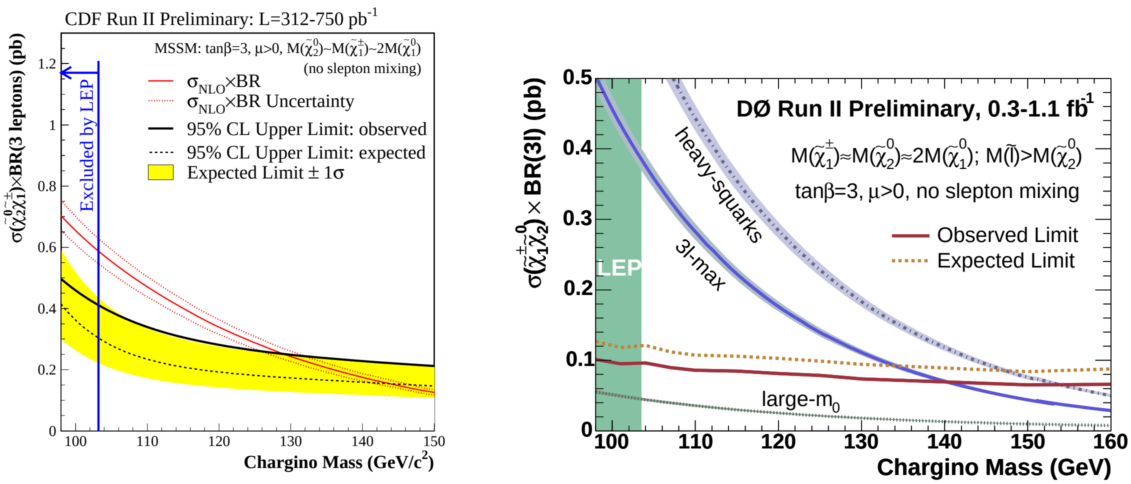


FIGURE 2. Limit on the associated $\tilde{\chi}^{\pm}\tilde{\chi}_2^0$ production cross section times branching fraction into three leptons by CDF (left) and DØ (right). Theoretical expectations in various mSUGRA scenarios are also indicated.

of light squarks leads to (at least) two jets; the pair production of light gluinos leads to (at least) four jets; the associated production of a squark and a gluino of similar masses leads to (at least) three jets. The reason for the "(at least)s" is that initial or final state radiation tends to increase the jet multiplicity. The possibility of cascade decays such as $\tilde{q} \to q'\tilde{\chi}^{\pm}$ complicates the picture, and a specific model such as mSUGRA is therefore needed to interpret the search results.

The main backgrounds in a search for multijets with missing E_T are

- instrumental, from QCD multijet production with fake missing E_T due to jet energy mismeasurements,
- from the associated production of W and jets, with $W \to \ell\nu$ where the lepton is not identified,
- from the associated production of Z and jets, with $Z \to \nu\nu$, which constitutes an irreducible background.

The CDF analysis was optimized for the configuration where the squark and gluino masses are similar, while DØ developed three analyses optimized for different hierarchies of squark and gluino masses. The main selection criteria are for each analysis a minimum number of jets, a minimum missing E_T, a minimum value for H_T, the sum of jet transverse energies, a veto on isolated leptons, and topological cuts on the angles between the missing E_T and jet directions. In 370 pb^{-1}, the CDF analysis selected two events for a background expectation of 8.2 ± 2.9 events. The three DØ analyses selected 18 events altogether in 310 pb^{-1}, for a total background expectation of 19.0 ± 5.3 events.

To turn these results into exclusion domains in the plane of the squark and gluino masses (Fig. 3), the mSUGRA framework was used, with mass degenerate light-flavor squarks. The results from the two collaborations are not directly comparable because DØ handles the theoretical uncertainties on the production cross sections in a somewhat

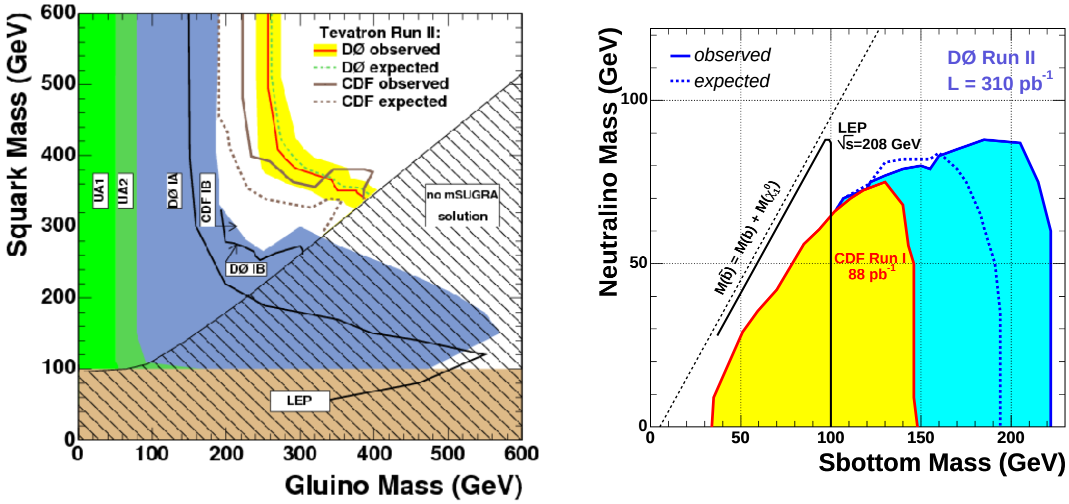


FIGURE 3. Excluded domains in the plane of generic squark and gluino masses (left), and in the plane of the sbottom and $\tilde{\chi}_1^0$ masses (right).

more conservative way than CDF (lower edge of the light shaded band in Fig. 3). Taking the CDF and DØ results as quoted by the authors, mass lower limits of 241 and 325 GeV are obtained for gluinos and squarks, respectively, and of 387 GeV for equal-mass squarks and gluinos.

Third generation squarks [5, 6]. Because of the impact of the large top Yukawa coupling on the renormalization group equations, the stop squarks can be expected to be lighter than generic squarks. Furthermore, the mixing in the stop mass matrix is also enhanced by the large top quark mass, so that the lighter stop could well be the lightest of all squarks, which justifies dedicated searches. The DØ collaboration has considered two scenarios

- a stop NLSP with a $\tilde{\chi}_1^0$ LSP, in which case the decay mode is the flavor changing process $\tilde{t} \to c\tilde{\chi}_1^0$,
- a mass hierarchy involving a light sneutrino, so that the stop decays according to $\tilde{t} \to b\ell\tilde{\nu}$. (The subsequent $\tilde{\nu} \to \nu\tilde{\chi}_1^0$ decay involves only invisible particles.)

In the first scenario, stop pair production leads to an acoplanar jet final state similar to the one considered for generic squarks. The difference is that, in the mass range of interest, the jets are much softer, and therefore the QCD background larger. To overcome this difficulty, a soft heavy-flavor jet tagging is applied. The kinematic selection is optimized as a function of the stop and $\tilde{\chi}_1^0$ masses. For $m_{\tilde{t}} = 130$ GeV and $m_{\tilde{\chi}_1^0} = 50$ GeV, 60 events are selected while the SM background expectation is 59.4 ± 12.8 events. An excluded domain in the plane of the stop and $\tilde{\chi}_1^0$ masses is derived (Fig. 4).

In the second scenario, the final state consists of two leptons, two b jets and missing E_T. Two analyses were developed, one for the $e\mu$ channel and the other for the dimuon channel. Again, the kinematic cuts were optimized as a function of the stop and sneutrino masses. As an example, the number of events observed in the $e\mu$ channel for small $\tilde{t}$–$\tilde{\chi}_1^0$

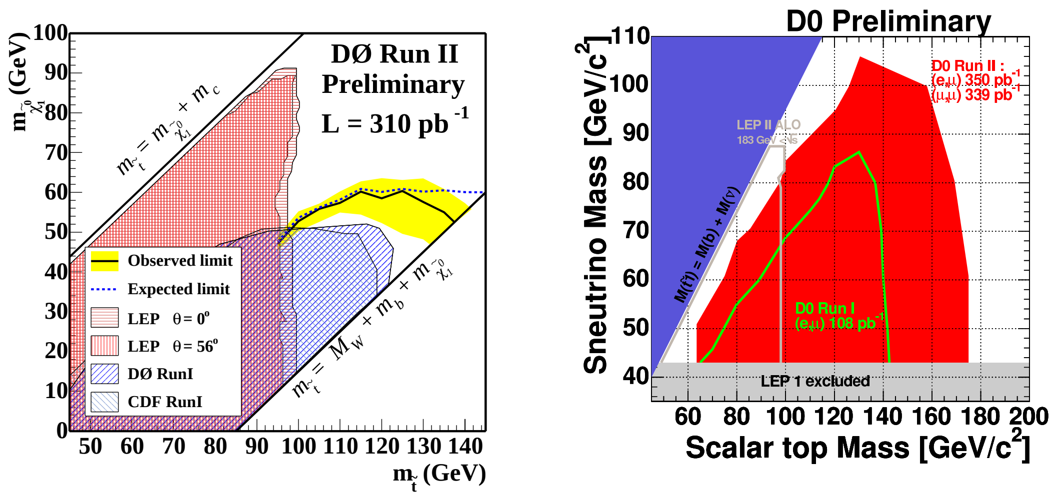


FIGURE 4. Excluded domains in the plane of the stop and $\tilde{\chi}_1^0$ (left), and stop and sneutrino (right) masses.

mass differences is 21, while the expected background is 23.0 ± 3.1. The two channels were combined to yield the excluded domain in the plane of the stop and sneutrino masses shown in Fig. 4.

Mixing can also be enhanced in the sbottom sector for large values of $\tan\beta$. A search for sbottom pair production was performed by DØ, where the $\tilde{b} \to b\tilde{\chi}_1^0$ decay is assumed. The analysis is similar to the one applied for the stop search in acoplanar jets, except that a tight b tagging can be applied, which provides sensitivity to higher masses, as can be seen in the exclusion domain shown in Fig. 3. The CDF collaboration considered the mass hierarchy such that the gluino decays into $b\tilde{b}$. Gluino pair production therefore leads to final states consisting of four b jets and missing E_T. With 156 pb^{-1}, sbottom masses up to 240 GeV have been excluded in this specific configuration for gluino masses smaller than 280 GeV and for $m_{\tilde{\chi}_1^0} = 60$ GeV.

Supersymmetry with R-parity violation

The most general superpotential contains

$$W_{\text{RPV}} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

where L and Q are lepton and quark doublet superfields, E, U and D are lepton and quark singlet superfields, and i, j, k are generation indices. These lepton or baryon number violating terms are forbidden by R-parity conservation, but could be present provided they do not introduce unacceptably fast proton decay or flavor changing neutral currents. This is easily achieved if all but one of the trilinear couplings can be neglected. The CDF and DØ collaborations have considered a number of scenarios where this constraint is satisfied.

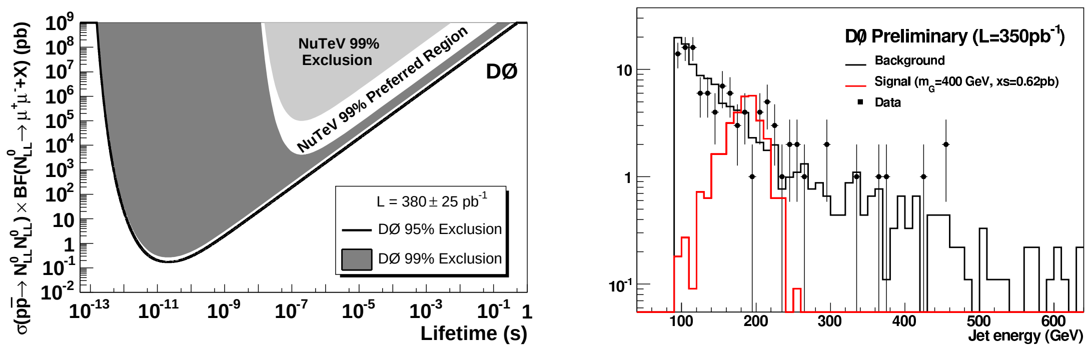


FIGURE 5. Upper limit on the production cross section times branching fraction into two muons for neutral long lived particles, as a function of the lifetime (left). Jet energy spectrum in the search for long-lived gluinos (right).

Pair production of gauginos was investigated by CDF and DØ, where the produced SUSY particle decays lead to two $\tilde{\chi}_1^0$ LSPs. With a λ_{121} coupling, for instance, the $\tilde{\chi}_1^0$s further decay into $ee\nu_\mu$ or $e\mu\nu_e$ and the final state therefore contains four electrons, three electrons and a muon, or two electrons and two muons, all with missing E_T taken away by two neutrinos. Searches for three leptons (electrons or muons) allowed the λ_{121} and λ_{122} couplings to be probed, and a dedicated search by DØ for two electrons and a hadronically decaying τ increased the sensitivity to a λ_{133} coupling [7]. Within the mSUGRA framework and for $\tan\beta = 5$ and large slepton masses, lower mass limits of about 120 GeV (105 GeV) were obtained by DØ (CDF) in the first two cases, using ~ 350 pb^{-1}. For a λ_{133} coupling, the search is most sensitive at large $\tan\beta$ and for light staus: a $\tilde{\chi}_1^0$ mass limit of 115 GeV was obtained by DØ for $\tan\beta = 20$ and $m_0 = 100$ GeV.

With a λ'_{211} coupling, resonant smuon or sneutrino production can occur via $q\bar{q}$ annihilation. In the case of smuon production, for instance, the smuon decays into a muon and a $\tilde{\chi}_1^0$, which in turn can decay through the same R-parity violating coupling into a muon and two quarks. The final state products, two muons and two jets, allow the $\tilde{\chi}_1^0$ and smuon masses to be reconstructed. The absence of accumulations for such masses in 380 pb^{-1} allowed DØ to set limits on the cross section for a resonantly produced smuon or sneutrino [7]. Since the production cross section depends on the value of the λ'_{211} coupling, mass lower limits were obtained as a function of this coupling. They range from 210 to 363 GeV for $\lambda'_{211} = 0.04$ to 0.10.

In the case of a λ'_{333} coupling, the $\tilde{t} \to b\tau$ decay is expected to occur. Stop pair production therefore leads to a final state containing two b jets and two τs. The CDF search for this topology selected two events in 320 pb^{-1} for an expected background of 2.3 ± 0.5 events, which lead to a lower stop mass limit of 155 GeV [6].

Finally, a search for neutral long lived particles decaying into two muons and a neutrino via a small λ_{122} coupling was carried out by DØ [7]. This search was motivated by three anomalous events in this topology observed by the NuTeV collaboration [8]. The DØ analysis selected 0 events with a dimuon vertex well displaced from the interaction point, while a background of 0.8 ± 1.6 events was expected. As shown in Fig. 5, such an interpretation of the NuTeV anomaly is excluded.

GMSB, AMSB and Split-SUSY [9]

In the framework of gauge mediated SUSY breaking, the NLSP is expected to be a stau or a neutralino. The latter case, where the NLSP decays into a photon and an invisible gravitino, was considered by DØ. Gaugino pair production ultimately leads to a final state containing two photons and missing E_T. The backgrounds from electrons or jets misindentified as photons or from fake missing E_T due to jet energy mismeasurements were all evaluated from data, leading to an expectation of 1.8 ± 0.7 events in 760 pb^{-1}, while four events were observed. The $\tilde{\chi}_1^0$ mass lower limit thus obtained is 120 GeV, improving on the result of a previous combination of CDF and DØ searches.

Anomaly mediated SUSY breaking predicts a wino LSP almost degenerate in mass with the lightest chargino, which may therefore well be long lived. Such a long lived charged massive particle would appear in a collider detector as a slowly moving muon. The timing information of the muon detector was used by DØ to search for the pair production of such particles, and no candidate events were found in 390 pb^{-1} while a background of 0.69 ± 0.05 events was expected. A chargino mass lower limit of 174 GeV was inferred.

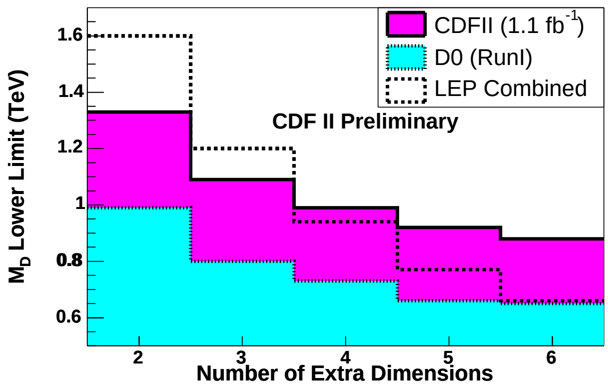
In split SUSY, a variant which recently received much attention, all scalars are very heavy, so that the gluinos become long lived. Such gluinos will hadronize into R-hadrons and may come to rest in the DØ calorimeter. After a while, they decay into a gluon and a $\tilde{\chi}_1^0$. The final state therefore appears as a jet with a random orientation in an otherwise empty event. The backgrounds from cosmic or beam-related muons were evaluated from data, and the predicted jet energy spectrum was found to be well consistent with observation (Fig. 5). For $m_{\tilde{\chi}_1^0} < 100$ GeV, a gluino mass lower limit of 300 GeV was deduced.

Indirect limits

The $B_s \to \mu^+\mu^-$ decay is strongly suppressed in the SM, at the level of 3 to 4 10^{-9}. A large enhancement is however expected in SUSY at large $\tan\beta$, proportional to $\tan^6\beta/m_A^4$. To overcome the huge background from SM dimuon production, CDF used a discriminant based on the decay length between the primary and dimuon vertices, the isolation of the dimuon system, and the pointing of that system toward the primary vertex. One candidate event was selected in 780 pb^{-1}, while 1.4 ± 0.4 background events were expected. The normalization was provided by the well measured branching fraction of $B^+ \to J/\psi K^+$, with $J/\psi \to \mu^+\mu^-$. A 95% C.L. upper limit of 10×10^{-8} was obtained [10], which already provides significant constraints on SUSY at large $\tan\beta$ [11].

EXTRA DIMENSIONS

There are now many variants of models with additional space dimensions. Two such models have received particular attention at the Tevatron. The Arkani-Hamed, Dimopololos and Dvali model [12] involves a number of large extra-dimensions (EDs).



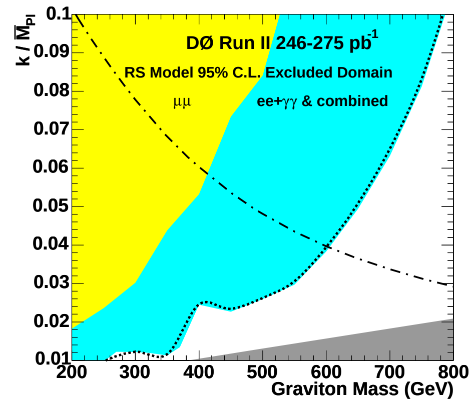


FIGURE 6. Lower limit on the fundamental Planck scale as a function of the number of large extra dimensions (left). Lower limit on the mass of an RS graviton as a function of its coupling to SM fields (right).

The Randall and Sundrum (RS) model [13] calls for a single ED with a warped metric. In both of these models, only gravity propagates in the EDs, and hence only the graviton has Kaluza-Klein (KK) excitations.

The presence of large EDs can be probed in two ways:

- real KK gravitons are produced in association with a jet, the large number of kinematically accessible KK gravitons compensating for the smallness of the gravitational coupling. Here the final state topology is a monojet;
- virtual KK gravitons are exchanged in the production of fermion or vector boson pairs, thus interfering with SM production and modifying the observed cross sections.

The CDF collaboration updated their search for monojets with 1.1 fb^{-1}. A jet with $E_T > 150$ GeV was required, allowing for soft additional jets. The missing E_T, in excess of 120 GeV, was required not to point along any jet direction, and a veto on isolated leptons was required. The predicted background, dominated by $(Z \to \nu\nu)$+jet, amounted to 819 ± 71 events, while 779 events were selected. Limits on the fundamental Planck scale M_D were derived as a function of the number of EDs as shown in Fig. 6 [2].

To search for virtual effects from large EDs, DØ combined the dielectron and diphoton final states and looked for deviations of the SM prediction at large masses, combining the information from the mass spectrum with the angular distribution of the electrons and photons. Their results, based on 200 pb^{-1} and expressed in terms of an effective cutoff M_S expected to be closely related to M_D, remain the most constraining to date. In the formalism of Giudice, Ratazzi and Wells [14], they obtain $M_S > 1.43$ TeV after combining with the DØ Run I result.

In the case of the RS model, the KK excitations have spacings of the order of a TeV, and can be observed as dielectron, dimuon or diphoton resonances. Combining those channels, the DØ collaboration has set a mass lower limit on the first RS KK graviton as a function of its coupling $\kappa/M_{\rm Pl}$ to the SM fields (Fig. 6).

MODEL INDEPENDENT SEARCHES

The CDF collaboration performed a series of "signature-based" searches, where possible departures from the SM predictions are looked for, irrespective of any specific theoretical prejudice [15]. Examples of such searches are analyses of the channels $\gamma\gamma$+X, where X is an electron, a muon or a photon, or $\ell\gamma$+missing E_T ($\ell = e$ or μ), the latter being motivated by an excess observed in the Run I data. All numbers of events and kinematic distributions were found to be in agreement with the SM expectations.

FINAL REMARKS

The CDF and DØ collaborations have now begun to explore truly virgin territories. By the time of this conference, already 1.4 fb^{-1} had been recorded by each experiment, only partially deciphered. With a steadily improving performance of the Tevatron collider, there are still a number of years and fb^{-1} of frontier physics ahead of us. Let's keep confident that results other than 95% C.L. limits will be presented at one of the forthcoming SUSY conferences.

ACKNOWLEDGMENTS

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